Akshay Kumar Chakravarthy *Editor*

Innovative Pest Management Approaches for the 21st Century

Harnessing Automated Unmanned Technologies

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Editor
Akshay Kumar Chakravarthy
Society for Science and Technology Applications (SSTA)
Bangalore, Karnataka, India

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Foreword

In agriculture, transfer of technology and knowledge to farmers, consumers and policy-makers is vital in achieving sustainable food production. In advanced countries, farmers and consumers are well informed and remain connected. This is of critical importance to farmers in developing countries as well. Thus, a comprehensive book embracing information on modern tools and communication technologies together with advances in pest management strategies was thoughtful and worthwhile.

The book *Innovative Pest Management Approaches for the 21st Century: Harnessing Automated Unmanned Technologies* is prepared following a three-tier system. The first part "Pest Population Monitoring: Modern Tools" consists of ten chapters dealing with newer gadgets and advances in technologies to detect pest populations in cultivated tracts and assess their severity. Technologies associated with satellites, remote sensing, smart mobile sets, smart pheromone traps, smart light traps, radar, LiDAR, drones and UAVs should become a part of an integrated pest management programme implementable on an area-wide scale. In addition, this part comprises four diverse chapters that go together to form the current advances in the science of crop protection. Host-plant resistance, light traps, artificial diet designs and info-chemicals can aid in developing practicable solutions to pest situations. The second part consists of emerging streams of application in pest management like endophytes, insect vectors, biopesticides, nanotechnology, soil biology, NPV, tropical forest pests, hymenopteran parasitoids and non-chemical management tools. These chapters mention the selection of new molecules and techniques that in the future can be rendered practicable and suitable for execution in the farmers' fields. The third tier or part comprises five chapters dealing with protected cultivation, nematode pests, IPM in vineyards and litchi orchards. They reveal certain new advancements and discoveries that have gone into the making and adoption of the current IPM strategies by growers.

This book will be particularly useful as it includes exceptional technical advancements and innovations for detecting and assessing the potential damage pests can cause to crops and incur yield losses. New procedures, processes and materials in biology are required in the future from the long-term perspective of rendering pest management practicable. This is crucial for scientists, policy-makers and growers. Smart materials, artificial intelligence, big data and cloud computing are some of the concepts very much relevant at the moment to train students and youngsters interested in pest management. With this book, key digital tools for transboundary plant pests monitoring and management and pest risk assessment in large cultivated land mass can be ascertained. Capacity development for area-wide pest management can be affected.

This integrated compact volume will kindle interest in crop protection research workers to take forward newer and safer technologies to farmers without jeopardising the environmental quality. It is hoped that the book will ignite and bring together scientists and technocrats from diverse backgrounds and also help countries to coordinate future actions and resources for monitoring pest populations assiduously worldwide.

Faculty of Agriculture, Department of Plant Protection Remzi Atlihan
University of Yuzuncu Yil,
Van, Turkey

Preface

Integrated pest management (IPM) approaches to tackle pests are varied and many. The pest suppression methods as a package keep changing over time. Several books in entomology, pathology and allied sciences have documented the proven pest suppression effective methods individually or in an integrated manner. Currently, scientists are focusing on pest management tools that act on insect system selectively, compatible with the environment and beneficial in the ecosystem; biocontrol, biopesticides, botanicals and mechanical and cultural tools fall under this framework. Other approaches deal with targeting biochemical and physiological aspects of insect metabolism involving biotechnological and genetic manipulations. There are other streams of approaches like the use of nanotechnology, endophytes and optical and sound manipulations that detect and control pest insects. So man has several pest management approaches in his arsenal to attack pests. But the cultivated landmass covered and the way the methods are executed in the field are equally important. Growers world over, especially in underdeveloped and developing countries, are still losing the battle against pests. This is because most farmers are not only knowledge- and technology-deficient, but also the information available on management practices to contain pests and pathogens does not reach them or reach so late that the farmers are unable to afford any protection. The pest control methods should be rapid and effective. There are communication and infrastructure gaps as well. Conventional ways of communication and technology transfer often do not facilitate information to the ground-level workers and farmers to reach in time. As a result, farmers are incurring huge crops losses and income. Key digital tools like satellites, remote sensing, smart mobiles, YouTube, LiDAR, drones and UAVs are required for tracking pests in cultivated tracts and transboundary areas. So, the book *Innovative Pest Management Approaches for the 21st Century: Harnessing Automated Unmanned Technologies* is needed.

Remote sensing is the science of sensing objects without coming in contact or touching them. The medium of interaction then is through electromagnetic radiation. To do this, a variety of tools/gadgets with high degree of sensitivity are required. An application-driven, Indian satellite programme, for instance, began in 1979 with the launch of remote-sensing satellite Bhaskara–I. Since then, tremendous advances in sensors in different parts of the electromagnetic spectrum, ultraviolet remote sensing, Rayleigh scattering, laser systems, signal and data processing, etc. have been incorporated into the airborne vehicles. The science of unmanned vehicles is still evolving!

The book is organised in three parts. The first part, “Pest Population Monitoring: Modern Tools”, contains ten chapters. Six chapters address issues concerning long- and short-range pest population monitoring techniques and tools like the use of satellites, unmanned aerial vehicles/drones, remote sensing, digital tools like GIS, GPS for mapping, LiDAR and use of mobile apps and software systems. UAVs have many applications in crop protection. One chapter exclusively deals with pesticide applications. Another chapter deals with pest surveillance, monitoring and management. The other four chapters deal with diverse streams of management approaches to contain pest populations, namely plant resistance; optical cues, in the form of light traps to attract and kill pests; artificial diet designs; and functional diversity of info-chemicals.

The second part of the book is devoted to “Emerging Arenas in Pest Management” that contains nine chapters. This will give the readers a glimpse of diversified tactics that have been developed to contain and suppress pest populations. This volume, however, does not include all streams of implementable ideas but deals with areas as soils and sustainable agriculture, pests of tropical forests, avoiding pesticides in tea ecosystems, endophytes, insect vectors of phytoplasma, hymenopterans, parasitoids, mass production and utilisation of NPV, role of biopesticides in horticulture pest management and nanotechnology.

The third part of the book concerns with “Integrated Pest Management”. In this part, five frontier aspects/systems, namely grape vineyard, role of coccinellids, litchi pests, protected cultivation and nematode pest management, have been dealt with. This part presents farming situations that illustrate how research in diversified aspects lead to finding solutions to certain pest problems and how some new and evolving tactics can be rendered practicable. This is to ensure that in the long run, the area becomes pest-free.

It was a difficult task to collect, organise and synthesise in a concise form the different chapters that have been included to form this book. The authors, experts in different aspects of a topic, had to be brought on to a common platform to write the chapters in a manner understandable to an audience with different and diverse backgrounds.

Bangalore, India Akshay Kumar Chakravarthy

Acknowledgement

I am extremely thankful to several of my colleagues, scientists, biologists and data analysts who helped in developing and producing this book. The idea to produce a book of this nature was conceived with all scientists 4 years before. I wish to express my gratitude to Prof. S. N. Omkar, Prof. K. N. Ramesh, Prof. V.K. Aatre, Prof. Muddu Shekar, Prof. N.V. Maslekar, Mr. Kiran P. Kulkarni and Mahavir Dwivedi for taking initiative on aerospace gadgets and vehicles suitable for monitoring pest populations in cultivated tracts. They kindled, nurtured and sustained my interest and ideas on advanced aerospace technologies applicable to agriculture, especially crop protection.

Prof. Omkar and Ramesh from Indian Institute of Science, Bangalore, along with Dr. Subhash, S., ICAR-Central Potato Research Institute, Shimla, contributed a chapter on the use of satellite and unmanned aerial vehicles (UAVs) for monitoring pest populations. Mr. Maslekar and Kiran Kulkarni too wrote a chapter on the above topic but focusing on altogether different aspects. Dr. Prasanna Kumar and Dr. Andt Kumar (Sri Lanka) together with Dr. P. N. Guru contributed a chapter on near-field remote sensing for pest population monitoring. Prof. Nagheswar Rao and Dr. B.P. Lakshmikanta collaborated for a chapter on the application of geospatial technology in plant health management.

LiDAR systems have unique advantage for crop protection, and these have been brought out by Mahavir Dwivedi, Malik and Santosh V. R. (Sweden). Mobile apps are particularly becoming popular in getting information on not only crop protection but everything and anything needed for agribusiness. They have become almost indispensable for everyone! Drs. Selva Narayanan, Sarvanaraman, Muthukumaranan and Jobichen Chacko (Singapore) have together explored the use of insect-resistant crop varieties for pest management. Dr. Rani, Dr. Vasudev Kammar and Dr. Jagadish K. S brought out salient advances in light traps and their use for monitoring pests. Authors Dr. Anjali Kumari Prasad and Dr. Ananda Mukhopadhyay contributed a chapter on artificial diet designing for tea pests. Dr. Kamala Jayanthi, P.D. Raghava, T. Vivek Kempraj and Byrappa Ammagarahalli are actively pursuing research on semiochemicals for pest management. They took a time off to contribute a chapter for this volume!

Over 20 entomologists devoted their valuable time to complete the second part of the book concerning “emerging arenas in pest management”. This part covered a wide range of themes—from soil pests (Drs. N. G. Kumar and Byrappa

Ammagarahalli) and forest pests (Prof. C. T. Ashok Kumar and Rema Devi) to hymenopterans parasitoids (Dr. Ankita Gupta), NPV (Drs. Gayathri, Doddabasappa and Rajashekar), insecticide toxicity and pesticide residues (Mahapatro and Rajna), nanotechnology (Dr. Atanu Bhattacharya), endophytes (Drs. Swapan Ghosh and Malavika Chaudhury, Manjunatha, N.) and a volley of new and emerging areas as insect vectors (Drs. Nagaraju, N.; Kavyshri, V.V.; and Thimmanna).

The third part of the book directly relates to integrated pest management modules executed in grapes (Sunitha, N. D. and Jose Luis), litchi (Kuldeep Srivastava, R.K Patel, Alok Kumar Gupta and Devinder Sharma), protected cultivation (Sridhar, V., and Nitin. K.S., P Swathi), nematode pests (Drs. M. S. Rao, Umamaheshwari and N.V. Maheshala), and coccinellid predators (Ahmed Pervez and Omkar).

I am grateful to all the contributors; without their help and cooperation, this book would have not been completed. While editing, I realised that diverse aspects across disciplines in chapters had to be rendered cohesive and well-blended. So the task of making chapters comprehensive and up-to-date required much time and effort. For this purpose, all the contributors solicited support and valuable inputs. I once again sincerely thank them all. The editor and contributors of chapters in this book sincerely thank the publishers, editors and authors of websites, online sources and other source materials for select figures and photos for noncommercial use.

The publisher, Springer, is aware and value quick and precise dissemination of information to the needy target groups, especially the farmers world over. I thank them for their interest, effort and concern.

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Editor and Contributors

About the Editor

Dr. Akshay Kumar Chakravarthy, Head and Principal Scientist (ret.), Division of Entomology and Nematology, is the author of numerous books and over 300 scientific papers and 60 chapters on entomology and natural history. His interests include insects, birds, bats, rodents and mammals. With nearly four decades of experience in teaching and research, Dr. Chakravarthy has been the principal investigator for over 35 research projects. Holding a Ph.D. from Punjab Agricultural University and a fellow of the IARI, New Delhi, he is a member of several national and international scientific associations, referee, reviewer and editor for several national and international journals. A field-orientated, widely travelled biologist, Dr. Chakravarthy is actively investigating novel approaches to integrated pest management, host plant interaction, vertebrate pest management, biodiversity and environmental conservation issues. He is author of several significant book contributions on this theme.

Contributors

Bakola Rukayah Aminu-Taiwo National Horticultural Research Institute, Ibadan, Nigeria

Byrappa Ammagarahalli Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Suchdol, Prague, Czech Republic

C. T. Ashok Kumar Department of Agricultural Entomology, University of Agricultural Sciences, GKVK, Bengaluru, India

Atanu Bhattacharya Department of Inorganic and Physical Chemistry, Indian Institute of Science, Bangalore, India

Jobichen Chacko The National University of Singapore, Singapore, Singapore

Akshay Kumar Chakravarthy Society for Science and Technology Applications (SSTA), Bangalore, Karnataka, India

Malvika Chaudhary CABI-South Asia, New Delhi, India

M. K. Chaya Division of Entomology and Nematology, ICAR-Indian Institute of Horticultural Research, Bangalore, Karnataka, India

B. Doddabasappa College of Horticulture, University of Horticultural Sciences, Bagalkot, Kolar, India

Mahaveer Dwivedi Computational Intelligence Laboratory, Indian Institute of Science, Bengaluru, Karnataka, India

Timothy T. Epidi Department of Crop Production Technology, Niger Delta University, Wilberforce Island, Yenagoa, Bayelsa, Nigeria

B. N. Gangadhar Department of Horticulture, Horticultural University, Bagalkot, India

S. S. Gayathri Devi Centre for scientific Research and Advanced Learning, Mount Carmel College, Bangalore, India

Swapan Kumar Ghosh Multiplex Biotech Private Limited, Bangalore, India

H. R. Gopalkrishna Division of Floriculture and Medicinal Crops, ICAR-Indian Institute of Horticultural Research, Bangalore, Karnataka, India

G. Nuthana Grace Division of Entomology and Nematology, ICAR-Indian Institute of Horticultural Research, Bangalore, Karnataka, India

Alok Kumar Gupta ICAR—National Research Center on Litchi, Muzaffarpur, Bihar, India

Ankita Gupta Insect Systematics Division, ICAR-National Bureau of Agricultural Insect Resources (NBAIR), Bangalore, India
Division of Germplasm Collection and Characterization, ICAR-National Bureau of Agricultural Insect Resources (NBAIR), Bangalore, India

P. N. Guru ICAR-Central Institute of Post Harvest Engineering and Technology, PAU Campus, Ludhiana, Punjab, India

Gautam Handique Department of Entomology, Tocklai Tea Research Institute, Jorhat, Assam, India

Mallikarjun M. Harsur ICAR-NRC on Pomegranate, Solapur, Maharashtra, India

K. S. Jagadish UEC, UAS, GKVK, Bengaluru, India

P. D. Kamala Jayanthi Division of Entomology and Nematology, ICAR-Indian Institute of Horticultural Research, Bangalore, Karnataka, India

Vasudev Kammar Department of Food and Public Distribution, Ministry of Consumer Affairs and Food and Public Distribution, Government of India, New Delhi, India

M. Kannan Division of Agricultural Entomology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

V. V. Kavyashri Department of Plant Pathology, University of Agricultural Sciences-GKVK, Bangalore, India

Vivek Kempraj Department of Biological Sciences, Macquarie University, Sydney, NSW, Australia

Ramesh Kestur Department of Aerospace Engineering, Indian Institute of Science, Bengaluru, Karnataka, India

Kiran P. Kulkarni Haribon Aeronautics, Bangalore, Karnataka, India

K. P. Kumar Department of Agricultural Entomology, University of Agricultural Sciences (UAS), Gandhi Krishi Vignana Kendra (GKVK), Bengaluru, Karnataka, India

N. G. Kumar Department of Agricultural Entomology, University of Agricultural Sciences, GKVK, Bangalore, Karnataka, India

A. N. D. T. Kumara Crop Protection Division, Coconut Research Institute, Lunuwila, Sri Lanka

B. P. Lakshmikantha Karnataka State Remote Sensing Application Centre (KSRSAC), Bengaluru, Karnataka, India

H. C. Loc Plant Protection Division, Southern Horticultural Research Institute (SOFRI), Tien Giang, Vietnam

Jose Luis Espinoza Villalobos, Evergreen Argo SAC, Lima, Peru

G. K. Mahapatro Division of Entomology, ICAR—Indian Agriculture Research Institute, New Delhi, India

N. Manjunatha Murdoch University, Perth, WA, Australia

N. V. Maslekar Sattva eTech PVT LTD, Bangalore, Karnataka, India

Ananda Mukhopadhyay Department of Zoology, University of North Bengal, Darjeeling, West Bengal, India

N. Muthukumaran Department of Entomology, Annamalai University, Chidambaram, Tamil Nadu, India

N. Nagaraju Department of Plant Pathology, University of Agricultural Sciences-GKVK, Bangalore, India

P. P. Nageswara Rao Karnataka State Remote Sensing Application Centre (KSRSAC), Bengaluru, Karnataka, India

M. V. Nataraja Department of Entomology and Plant Pathology, North Carolina State University, Raleigh, NC, USA

K. S. Nitin Department of Conservation and Marine Sciences, Faculty of Applied Science, Cape Peninsula University of Technology, District Six Campus, Cape Town, South Africa

Omkar Ladybird Research Laboratory, Department of Zoology, University of Lucknow, Lucknow, India

S. N. Omkar Department of Aerospace Engineering, Indian Institute of Science, Bengaluru, Karnataka, India

S. Onkara Naik Division of Entomology and Nematology, ICAR-Indian Institute of Horticultural Research, Bangalore, India

R. K. Patel ICAR—National Research Center on Litchi, Muzaffarpur, Bihar, India

Ahmad Pervez Department of Zoology, Radhey Hari Government P.G. College, Kashipur, Uttarakhand, India

Anjali Km. Prasad Entomology Department, Tocklai Tea Research Institute, Tea Research Association, Jorhat, Assam, India

N. R. Prasannakumar University of Greenwich, Old Royal Naval College, London, UK

T. Raghava Division of Entomology and Nematology, ICAR-Indian Institute of Horticultural Research, Bangalore, Karnataka, India

S. Rajashekara Department of Zoology, Bangalore University, Bengaluru, India

S. Rajna Division of Entomology, ICAR—Indian Agriculture Research Institute, New Delhi, India

A. T. Rani Division of Crop Protection, ICAR-Indian Institute of Vegetable Research (ICAR-IIVR), Varanasi, Uttar Pradesh, India

M. S. Rao Division of Entomology and Nematology, ICAR-Indian Institute of Horticultural Research, Bangalore, Karnataka, India

O. K. Remadevi Centre for Climate Change, Environmental Management and Policy Research, Institute (EMPRI) "Hasiru Bhavana", Bangalore, India

Somnath Roy Department of Entomology, Tocklai Tea Research Institute, Tea Research Association, Jorhat, Assam, India

V. R. Santosh Unit of Chemical Ecology, Department of Plant Protection and Biology, Swedish University of Agricultural Sciences, Alnarp, Sweden

M. Saravanaraman Department of Entomology, Annamalai University, Chidambaram, Tamil Nadu, India

V. Selvanarayanan Department of Entomology, Annamalai University, Chidambaram, Tamil Nadu, India

Malik Hashmat Shadab CINT Lab, Indian Institute of Science, Bangalore, Karnataka, India

Devinder Sharma Division of Entomology, SKUAST-J, Jammu, Jammu and Kashmir, India

V. Sridhar Division of Entomology and Nematology, ICAR-Indian Institute of Horticultural Research, Bangalore, India

Kuldeep Srivastava ICAR—National Research Center on Litchi, Muzaffarpur, Bihar, India

S. Subhash Division of Plant Protection, ICAR-Central Potato Research Institute, Shimla, Himachal Pradesh, India

N. D. Sunitha Division of Entomology, College of Agriculture, UAS, Dharwad, Vijayapura, Karnataka, India

P. Swathi Division of Entomology and Nematology, ICAR-Indian Institute of Horticultural Research, Bangalore, India

Thimmanna Department of Plant Pathology and Nematology, Indian Agricultural Research Institute, New Delhi, India

R. Umamaheswari Division of Entomology and Nematology, ICAR-Indian Institute of Horticultural Research, Bangalore, Karnataka, India

M. G. Venkatesha Department of Zoology, Bangalore University, Bengaluru, India

Part I

Pest Population Monitoring: Modern Tools

Applications of Geospatial Technologies in Plant Health Management

1

P. P. Nageswara Rao and B. P. Lakshmikantha

Abstract

In this chapter, an overview of remote sensing applications for pest management and plant protection is presented. The flow and gaps in the existing organization of plant protection information are highlighted. Methods of integration of remotely sensed data into the conventional plant protection and crop assessment system are addressed. Crop pests and diseases commonly occurring in continuous cropping pattern zones, whose symptoms are amenable to remote sensing, are dealt with. Numerous economically important crop pests/diseases are sporadic in time and space, but they are not included in this chapter. The objective of this chapter is to create basic awareness for the possibility of using remotely sensed data for pest detection and plant protection. This will also enthuse further thinking to make this emerging area of application operational in the years to come.

Keywords

Remote sensing · Plant protection · Plant health management · Integrated pest management

1.1 Introduction

Remote sensing is a technique of measurement or acquisition of information on property of an object or phenomenon by a recording/measurement device that is not in physical contact with the object or phenomenon under study. The term plant protection has been adopted by the Food and Agriculture Organization (FAO) of the

P. P. Nageswara Rao · B. P. Lakshmikantha (✉)
Karnataka State Remote Sensing Application Centre (KSRSAC), Bengaluru, Karnataka, India

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United Nations (UN) and is used as a general designation for all the crop protection and plant pest management disciplines.

Remote sensing measurements make use of the visible, infrared and microwave sensors with specific spatial and radiometric characteristics in the acquisition of required data. Photography and videography from ground, unmanned aerial vehicles (UAV), aircrafts and satellite-borne photography, multispectral scanning and imaging are common platforms. Also, ground-based and airborne radar and acoustic sounding are some of the other techniques of remote sensing applicable in plant protection. The data thus acquired is stored in the form of photographs, images or digital tapes depending on the sensor used and the mode of acquisition. The data is interpreted either manually, machine-assisted or totally automated and the information thus obtained is used for inventory, survey, monitoring, planning and management of crop pests and diseases. Remote sensing is especially useful where speed, repetitive observations and a synoptic view are required. It provides an important new dimension for the detection and quantification of damage to plants, assessment of the distribution of the principal host plants or habitats of insect pests, surveillance of environmental factors favourable for the development and spread of insects and pathogens.

An attempt is made in this chapter to apprise the plant protection community on the potentials of remote sensing, particularly while integrating it with the conventional system. In doing so, the principles of agricultural remote sensing, the magnitude of crop losses, the symptomatology and weather conditions associated with the outbreak of crop pests and diseases are discussed. This chapter describes how remote sensing techniques have been applied in three distinct areas of application: the observation of crop pests/diseases themselves, the detection of the effects they produce and the monitoring of environmental factors likely to influence their behaviour.

Current advances in remote-sensed imagery and geospatial image processing using unmanned aerial vehicles (UAVs) have made recognition and monitoring of pests easy and precise. For instance, Vanegas et al. (2018) described a method for detecting pest populations and crop damage against grape phylloxera in vineyards. Developing such devices has provided researchers with reliable data rapidly on grape phylloxera (*Daktulosphaira vitifoliae* Fitch). Miniaturized imaging technology for small UAVs and small area inspections at cheaper rates is enabling small marginal farmers to adopt imaging technology (Näsi et al. 2015). Norway spruce (*Picea abies* (L.) *H. Karst*.) suffer from bark beetle (*Ips typographus* L.) damage. The processing method in forests and for individual trees can be applied with an accuracy of 95% (Näsi et al. 2015). Lan et al. (2010) reviewed the aerial application of chemicals in agricultural landscapes in the USA. Variable-rate aerial application provides a means for delivering chemicals as much as growth regulators, defoliators and pesticides. Variable-rate control implies sprays over field areas that require/do not require inputs based on global positioning or applying variable rate to meet the varying need of the farmers. Maps for the aerial application have been developed using remote sensing, global positioning and geographic information system technology. Remote sensing is a technique that utilizes a tool to measure and record a change in electromagnetic radiation and enables better means of quantifying biotic stress (Rani et al. 2018).

1.2 The Need for Remote Sensing in Plant Protection

Factors influencing crop production can be divided into three schematic groups: yield-defining factors such as radiation, yield-limiting factors such as the availability of water and nutrients, and yield-reducing factors such as crop pests. Any living organism that causes harm to man and his crops or animals by virtue of their abnormal increase in numbers, qualifies for being called a pest. Insects, diseases, weeds, rodents and nematodes, all can be called by the common word "pest". The plant protection encompasses a myriad of activities, viz., quarantine regulations, determination of economic thresholds of pests, epidemiology, life cycles of pests and understanding of the ecological conditions in the agroecosystem. The need for remote sensing technology lies in providing useful information on these factors and to bridge gaps in existing systems securing the information-flow in plant protection.

1.2.1 Nature and Magnitude of Crop Losses

The response of vegetation to stress (pest and disease attacks, drought, nutrient deficiency) can be in the form of change in leaf area, leaf pigments, and reduced physiological processes. Stress leads to a reduction in yields. Yield-reducing factors can be either episodic in nature or a long-term process. Understanding the magnitude of crop losses is necessary to appreciate the importance of plant protection in crop production programmes. Crop losses can be due to biotic factors like insect pests/diseases/weeds and abiotic factors like drought, flood, cyclones and hailstorms. Damage caused by pests may be quantitative or qualitative. Based on the global literature, Cramer (1967) attempted to determine the cost of pests in agriculture. He estimated a 35% loss due to pests of potential production (13.8% due to insects, 11.6% due to diseases and 9.5% on account of weeds). In India, crop losses occur every year, the loss due to crop pests being approximately Rs. 50,000 million. These figures are indicative of the magnitude of the problem and make out a prima facie case for devoting more attention and importance to plant protection.

1.2.2 Changing Agroecosystems and Related Pest Problems

Recent changes in agricultural practices including the introduction of irrigation, fertilizers, high-yielding cultivars and new farming systems are unfortunately accompanied by changes and increases in pest problems. The increasing use of irrigation in the semi-arid tropics has a major effect on pest populations (Bald et al. 1978). Disease and pest problems are many times more in tropics than in the temperate region. Continuity of the crop (mono-cropping) and collateral hosts enable the easy perpetuation of pests. There is an obvious danger that pests such as *Heliothis armigera* Hubner an insect pest of pigeon pea, that gradually reduced to low population levels, its population increase if irrigated crops are available for long periods.

For example, irrigated tomatoes, which were virtually unknown a few years ago, are now regularly grown during each dry season. *H. armigera* utilizes these plants as a new host and builds-up its populations that attack other crops in the ensuing Kharif season. Another example is the brown plant hopper, *Nilaparvata lugens* Stal, a major pest only in the cooler rice-growing countries of Asia, viz., Japan, China and Korea. From 1970, when cultivation of high-yielding, irrigated and profusely tillering rice varieties became popular, this pest became a major threat to rice crop in India and other South-East Asian countries (IRRI (International Rice Research Institute) 1977).

1.2.3 Timeliness and Accuracy of Information

Timely information is of great value for agricultural disaster management; the data generated should preferably be processed well in advance so that the information obtained allows the farmers to take alternative measures and minimize the losses. The accuracy of information ensures confidence in the minds of decision makers at all levels and thus coordination of various activities become easy.

The information needs vary with each type of decision maker. The needs of a local farmer are different from those of a district agricultural officer, or a state level Directorate of Agriculture and national level planning body. A farmer desires to know the period of suitable weather conditions for his farm operations and the likelihood of weather favouring pest and disease outbreaks. At the district and state levels, the required information is on: (1) general agrometeorological conditions during the crop growing season, (2) delineation of areas for growing suitable crops based on the analysis of long-term agro-climatological parameters, (3) details of villages affected by pests and diseases, severity of damage, quantum of inputs required for the next crop, credit/subsidy facilities extended and the beneficiaries at major outbreaks of pests/diseases or natural disasters.

The regional disparities in crop condition assessment, the complex centre-state relationships in handling relief operations, the introduction of crop insurance schemes, call for an unbiased, objective and timely information system to (1) give early warning, (2) to indicate the intensity of impending agricultural hazard and (3) to assess the quantum of loss.

1.2.4 Organization of Plant Protection and Gaps in the Existing System

At the international level, the Food and Agriculture Organization (FAO) of the United Nations has taken leadership in diverse aspects of plant protection, that embraces estimation of crop losses, organization of research on projects of global importance, initiation of new concepts in pest control, coordination of surveillance of desert locust amongst different countries, dissemination of information through bulletins, etc. Plant protection in India is mainly handled by the Directorate of Plant

Protection, Quarantine and Storage (DPPQ&S) and the Directorate of Agricultural Aviation under the Plant Protection Division, Ministry of Agriculture and Farmers Welfare. This division works in close cooperation with ICAR, Department of Chemicals, and the Ministry of Health. The DPPQS in collaboration with the State Departments of Agriculture and the Central Plant Surveillance and Plant Protection Stations keep watch on pest and disease situations. The Locust Warning Organization of DPPQS monitors the locust activities over about 0.26 million km^2 of the scheduled desert area in western India. The DPPQ&S provides training in plant protection at the Central Plant Protection Training Institute (CPPTI), Hyderabad. It is also involved in multiple activities and responsibilities. This kind of networking system is present in other countries of the world.

Each State and Union Territory has a separate plant protection organization. The Agriculture Departments and Agriculture Universities of the State provide necessary assistance to the growers in the control of pests. The State organization looks after plant protection works in all aspects—technical, supply, service and advisory. It has specific responsibilities in respect of enforcing the Insecticides Act, 1992.

The Indian Meteorological Department (IMD) through its Agricultural Meteorology (Agrimet) Division issues farmers' weather bulletins and broadcasts daily programmes over the rural radio and a weather report on TV. These give district-wise forecasts for 36 h with an outlook for the subsequent 2 days, the emphasis being put on those aspects of weather that are likely to affect crops. These forecasts are guided by the crop-weather calendars and warnings are issued during different phases of crop growth.

The Agrimet Division has been conducting research on agrometeorology and pests, viz. paddy stem borer, sorghum shoot fly, cotton bollworm, Pyrilla of sugarcane and wheat rusts. The Agrimet Division is actively associated with DPPQS in giving meteorological support to the locust control programme.

1.2.5 Gaps in the Existing System

There is no regular information about the area affected by pests and diseases and other yield-reducing factors on all India level. For a vast country like India, the estimation of crop production and assessment of prevailing conditions are difficult through surveys based on sampling. It is even more complicated if the estimates are made at different stages of crop growth. Generally, statistical estimates for plant protection are inadequate (Bansil 1984).

The "felt loss" concept commonly used in plant protection is highly subjective and difficult to be used by a village level worker. There are enormous variations in estimates both in space and time. Most of the available data on losses due to crop pests/diseases are from research stations farms where ecological conditions are not similar. The loss estimates due to crop pests/diseases, drought, flood and cyclone are further subjected to socio-economic-political decisions. Hence, the "subjective" nature of the estimates are further been vitiated. Figure 1.1 gives outline of an integrated approach to fill the gaps in crop loss assessment.

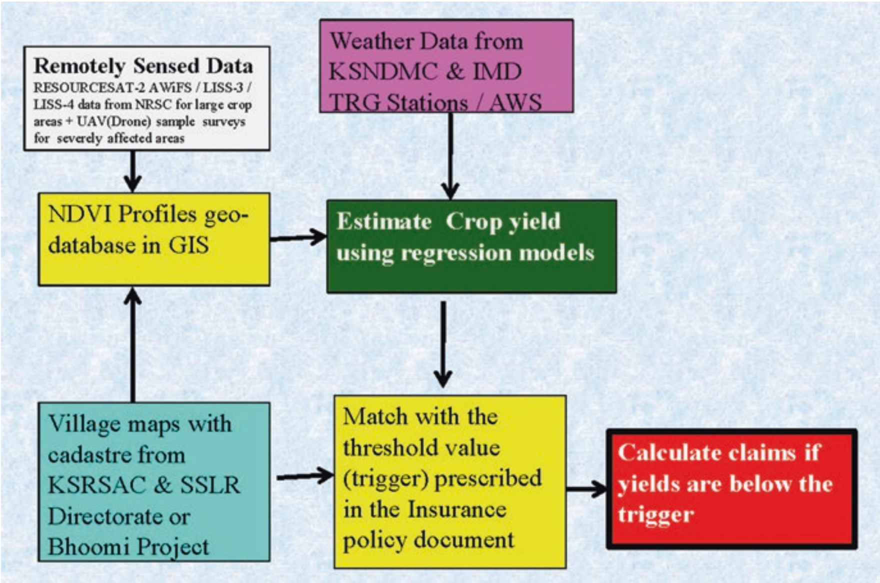

Fig. 1.1 Outline of crop loss assessment that can be adopted in future

The developed nations use agrometeorological forecasts to prevent losses, with the well-known notion that the loss prevented corresponds to the gain accrued. Weather forecasts of short to long range are useful in plant protection. Long-range forecasts based on established relationships of crop growth, the incidence of pests and diseases and the antecedent cumulative weather conditions help in planning plant protection measures. Short-range forecasts help in pesticide spraying, crop harvesting, etc. Meteorological parameters are routinely monitored, relevant agricultural information is not forthcoming for integration into an agrometeorological service. The meteorological warning usually covers a vast area and is therefore not applicable locally.

Certain crop pests and diseases may have their origin in the data-sparse geographical regions beyond the international boundaries. The desert locust is an example of this type. Similarly, certain weather systems like the western disturbances take their birth in neighbouring countries from which precise and appropriate data collection may be difficult.

1.3 Physical and Physiological Basis of Plant Health Assessment

1.3.1 Leaf Reflectance

An understanding of the physical and physiological properties of plants and their interaction with incident radiation is important in crop condition assessment through remote sensing. Typical spectral reflectance of crop/vegetation shows few striking features of the leaf reflectance: high absorptance in the blue (0.45 μm), the reduced absorptance in the green (0.55 μm), another high absorptance in the red (0.65 μm), the very high reflectance in the near-infrared (0.75–1.2 μm) and again very high absorptance in the far-infrared. The absorptance in the visible region of the electromagnetic spectrum is due to plant pigments (carotenoids, chlorophyll a and chlorophyll b). The energy absorbed by the plants in the visible region (0.4–0.7 μm) is called photosynthetically active radiation (PAR). The abrupt increase in reflectance near 0.75 μm is due to the internal structure of the leaf and canopy geometry. There are liquid-water-absorption bands at 1.40 and 1.90 μm. Leaf water is largely the cause of strong absorption throughout the far-infrared (1.13–2.5 μm).

Knipling (1970) stated that physiological disturbance to a leaf leads to an increase in leaf reflectance in the visible region and Cardenas et al. (1969) showed a rounding of a near-infrared reflectance plateau. Differences in the refractive indices of the hydrated cell wall (1.47) and air (1.0) of the intercellular spaces in the palisade parenchyma and spongy mesophyll layers of the leaf affected the leaf reflectance (Gausman 1974).

Tucker and Garratt (1977) treated the leaf optical system as a stochastic process and established a ten-compartment flow model. The model incorporates scattering and absorption processes as a function of wavelength. The same scattering mechanisms necessary in the absorption of the PAR for photosynthesis results in high values of leaf reflectance in the near-infrared region. Tucker (1978) reviewed the plant canopy physiology and stress detection by remote sensing and concluded that a 0.76–0.90 μm photographic infrared sensor would combine general vegetation monitoring with the ability to discriminate the infrared plateau rounding stress conditions. In a review, Grant (1987) concluded that leaves are neither purely diffuse nor purely specular reflectors. Leaves have both diffuse and specular characteristics. The specular non-Lambertian character of leaf reflectance arises at the surface of the leaf, primarily affected by the topography of the cuticular waxes and leaf hairs. Loss of infrared reflectance is one of the earliest symptoms of reduction in vigour in many plants (Colwell 1964).

At times of drought, spongy and palisade mesophyll cells become flaccid resulting in a reduction in the infrared reflectance. In fungal infection, the leaf air space may be invaded by fungal hyphae, further reducing the infrared reflectance from the leaves. Field reflectance (>0.5–2.4 μm wave band) for control and ozone-damaged Cantaloupe plant canopies were different statistically for the 1.45-, 1.65-, 1.95- and 2.2-μm wavelengths in the infrared water absorption region (Gausman et al. 1978). However, Lorenzen and Jensen (1989) showed that identification of barley powdery mildew by means of changes in spectral properties was earlier and more reliable in the visible region of the spectrum than in the infrared region, especially at wavebands centred at 0.49 and 0.66 μm. The differences in near-infrared (NIR) reflectance between healthy and infected plants were observed several days later, after the best time for beneficial fungicide treatment (Fig. 1.2).

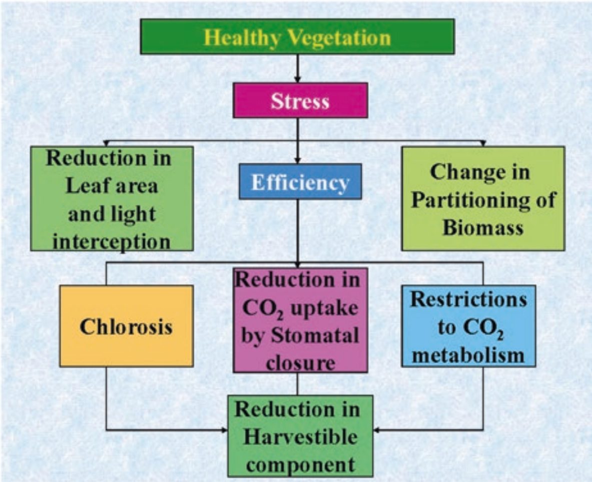

Fig. 1.2 Crop physical and physiological changes that occur during stress

1.3.2 Canopy Reflectance

An understanding of the overall canopy reflectance is necessary to determine the canopy architectural changes arising from stress and other factors. During the last decade, several canopy reflectance models have been proposed (Suits 1972; Goel 1982). All these models consider the canopy in terms of horizontal and vertical leaf facets with individual reflectance and transmittance. The leaf area index (LAI) and leaf inclination angle (LIA) distribution function are used to depict the canopy architecture. Ross and Marshak (1988) constructed a rather universal model of the plant canopy architecture containing the structural parameters and presented the Monte Carlo computational procedure to calculate the bidirectional reflectance distribution function. This model allows the determination of the role of leaf dimensions, plant height and distance between leaves on canopy reflectance. Crop canopy reflectance is affected by changes in foliage density, leaf area, leaf angles as a result of crop growth, development, stress and cultural practices.

1.3.3 Crop Canopy Temperature

Monteith and Szeicz (1962) were among the first to use radiation thermometry to measure canopy temperatures. They developed a theory relating canopy temperature to canopy stomatal resistance. Subsequently, canopy-air temperature differences (Tc-Ta) measured at the time of maximum surface temperature were used as an indicator of crop water status and crop yield (Idso et al. 1977). Jackson (1982) developed a crop water stress index (CWSI) based on the equations of Monteith and Szeicz (1962), which provides a rational basis for relating crop water stress and canopy temperatures. The most useful wavelength region for canopy temperature measurement and quantification is the thermal infrared band (8–14 μm). The crop canopy temperature can be measured both from aircraft and satellite platforms. Currently, Thematic Mapper (TM) of Landsat, Advanced Very High-Resolution Radiometer (AVHRR) on board the U.S. National Oceanic and Atmospheric Administration (NOAA) satellites and the Indian National Satellite (INSAT) provide data in thermal infrared channels.

1.3.4 Vegetation Indices

Rouse et al. (1973) developed a transformation of radiance values of NIR and red (R), the two contrasting spectral bands, and called it a vegetation index (VI). Colwell (1974) found that the NIR/R ratio was effective in normalizing the effect of soil background reflectance variations and was useful for estimating the biomass. Kauth and Thomas (1976) and Richardson and Wiegand (1977) have developed the greenness vegetation index (GVI) and the perpendicular vegetation index (PVI). Tucker (1979) evaluated the usefulness of VIs and concluded that the linear combinations of the red (0.63–0.69 μm) and photographic infrared (0.75–0.80 μm) radiances can be employed to monitor the photosynthetically active biomass, the vigour and the plant condition canopy. The original indices were based on combinations of visible and near-infrared bands, although other techniques have recently been proposed using microwave backscatter. Sellers (1985) found the ratio of NIR and visible reflectances to be a linear indicator of minimum canopy resistance (evapotranspiration) and photosynthetic capacity. But it is a poor predictor of leaf area index or biomass. Kumar (1988) showed that the relationship between NIR/R ratio and vegetation is curvilinear, it varies linearly with the fraction of photosynthetically active radiation absorbed by the vegetation. The study illustrates the importance of soil reflectivity at a small leaf area index (LAI), crop geometry at intermediate LAI and leaf reflectivity at a large LAI (Fig. 1.3).

The advent of high spectral resolution data from aircraft sensors has stimulated an interest in measuring the biochemistry of plant canopies using remote sensing techniques. Narrow-band (−10 nm) near-infrared reflectance measurements of plants have been used to develop empirical relationships for estimating protein, lignin, cellulose and starch contents of plant materials (Shenk et al. 1981). A lignocellulose dry vegetation index was developed using high spectral resolution AVIRIS (airborne visible infrared imaging spectrometer) data (Elvidge 1990). He observed diagnostic lignocellulose absorption features at 2.09 and 2.30 μm region and concluded that a valuable synergism may be available through the combined use of green and dry vegetation indices, useful in discriminating plant communities, phenological conditions and in identifying vegetation stress factors.

1.3.5 Vitality Indicator for Plants

Vegetation reflectance in the transition region from red to infrared reflectance between 670 and 760 nanometres (nm) spectral region, the so-called red edge, is a

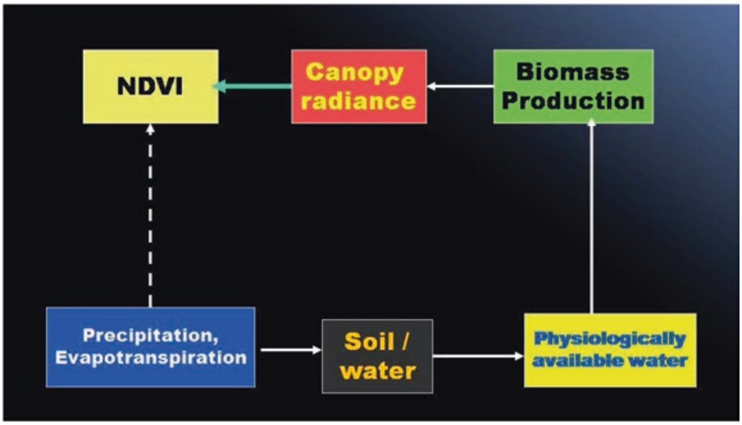

Fig. 1.3 Relationship between the normalized difference vegetation index (NDVI) and the agro-climatic conditions under which a crop is grown

good indicator of the biological status of plants. Many researchers found the shape of the red edge and the wavelength position of the inflection point (i.e. the shifts in the red edge either towards longer or shorter wavelengths) to be associated with increasing chlorophyll concentration during crop maturity (Collins 1978) or due to stress (Horler et al. 1983). A distinct shift of the red edge in reflectance spectra of sugar beet crops due to differences in leaf vitality was reported suppressing contributions of non-vegetative reflectance components. Boochs et al. (1990) have shown the spectral values derived from the red edge to be representative of crop management parameters. An inverted Gaussian model for the red edge reflectance was evaluated in the 670–800 nm region by Miller et al. (1990). Nisarga et al. (2019) observed a shift in red edge position (REP) of cotton crop (Fig. 1.4).

1.3.6 Chlorophyll Fluorescence as Stress Indicator

A portion of the light intercepted by a plant is absorbed by the photosynthetic pigments, creating a supply of singlet electronic excitation energy. Under optimal conditions, 85% of this energy is used in photosynthesis. The remainder is lost as heat or radiated as fluorescence. Fluorescence emanates mostly from the chlorophyll of photosystem 2 with a maximum at 685 nm. In general, weak chlorophyll typifies rigorous photosynthesis and strong chlorophyll, a weak or inhibited photosynthesis.

Under plant stress conditions, the electron transport in the photosynthetic unit (quantasome) is disturbed. The absorbed light is given off as radiation energy in the form of chlorophyll fluorescence and heat emission. Lichtenthaler (1988) gave a detailed account of applications of this phenomenon in stress physiology and remote sensing. When a normal green leaf is illuminated, the fluorescence rises to the ground level (fo) and then increases to a maximum (fm). With the onset of

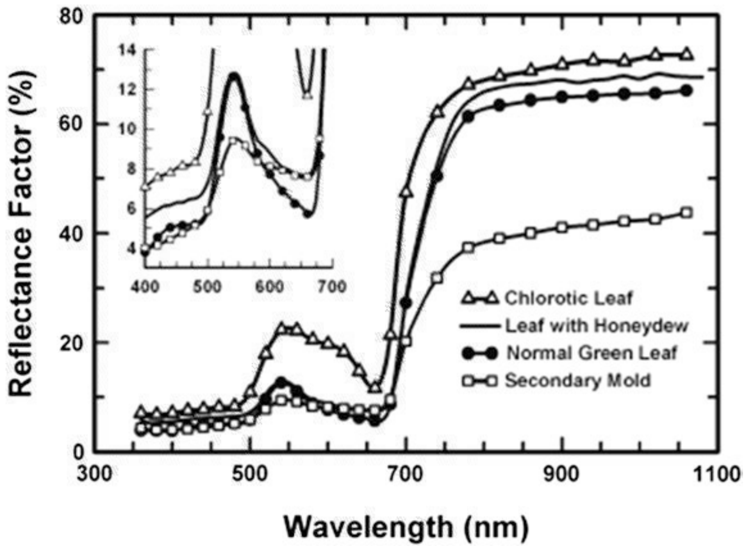

Fig. 1.4 Comparisons between hyperspectral reflectance factors of a normal green cotton leaf and a cotton leaf covered with honeydew produced by whiteflies (*Bemesia tabaci*), a leaf covered with a secondary mould *Aspergillus* sp. growing on the whitefly honeydew, and chlorotic leaf without honeydew. Data were acquired with a Spectron SE-590 spectroradiometer. Solar incidence angle was 45° to the leaf surface and viewing angle was normal to the leaf surface. (Source: Nisarga et al. 2019)

membrane energization and photosynthetic oxygen evolution, the fluorescence decreases slowly and reaches a steady-state level (fs). The fluorescence decrease from fm to fs is paralleled by increasing rates of oxygen evolution and photosynthetic CO_2-fixation. In the normal green leaf, with increasing chlorophyll content, the relative fluorescence at 690 nm becomes smaller than at 735 nm. Laser-induced chlorophyll fluorescence has already been applied with good success in assessing the physiological status of plants (Rock et al. 1986). Buschmann et al. (1991) reported the use of visible infrared reflectance absorbance fluorescence (VIRAF) spectrometer for detection of stress in coniferous forests. The VIRAF measurements proved an excellent tool of physiological ground-truth and vitality testing.

1.3.7 Image Interpretation and Spatial Data Analysis

For effective utilization of remote sensing for plant protection, it should enable identification of the crop type, the pest/pathogen responsible for the damage, determination of crop vigour and quantification of yield loss. This means the extraction of information from remotely sensed data either through visual interpretation or computer-aided image processing. Most often these two techniques are employed together. The identification of crops by photo-interpretation relies on a combination of objective and subjective decisions. Computers use a set of spectral pattern recognition techniques which make use of reflectance characteristics (spectral signatures)